5.8 DEVELOPMENT AND TESTING OF A SKY ARROW 650 ERA FOR ATMOSPHERIC RESEARCH

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1. INTRODUCTION

Airborne measurement of mass, momentum, and energy fluxes for boundary layer research has been available for decades, and until recently has required the use of large aircraft to carry instruments and dedicated support facilities to operate those aircraft. However, the advent of compact, low-power instruments and high speed, high-capacity digital data acquisition systems will now allow small aircraft to carry such instruments (Crawford *et al.* 2001). Until recently, the instrument packages for these aircraft (and in some cases the aircraft themselves) were most often custom built. The focus of this paper is to report on the development and testing of a new commercially available aircraft which is instrumented to measure fluxes of mass, momentum, and energy in the lowest levels of the atmospheric boundary layer. This aircraft is the Sky Arrow 650 Environmental Research Aircraft (ERA), produced by Iniziative Industriali Italiane Spa., and instrumented by NOAA's Atmospheric Turbulence and Diffusion Division. The first Sky Arrow 650 ERA is owned and operated by San Diego State University's Global Change Research Group. The aircraft was operated on the North Slope of Alaska measuring CO_2 and H_2O fluxes for the summers of 1999 and 2000.

2. EDDY-FLUX MEASUREMENT TECHNIQUE

The eddy-correlation technique is used to measure vertical fluxes of mass, momentum, and energy in the lower boundary layer. The technique relies on measurement of the ambient vertical wind component and the concentration of the species of interest. The eddy flux can be mathematically expressed as a covariance (Baldocchi *et al.* 1988):

$$F_\phi = \langle(\rho w)'\phi'\rangle \tag{1}$$

where $(\rho w)'$ is the vertical turbulent fluctuation of the product of dry air density and vertical wind component and ϕ' is the turbulent fluctuation in the mixing ratio of the species of interest. The angle brackets indicate the appropriate ensemble average.

3. WIND MEASUREMENT SYSTEM

Measuring the velocity of wind with respect to the Earth, **V**, from a moving platform such as an aircraft is accomplished by measuring two velocity vectors: $\mathbf{V}_a$, the velocity of air with respect to the aircraft, and $\mathbf{V}_p$, the velocity of the aircraft with respect to the Earth. The vectors are combined as shown in Eq. (2).

$$\mathbf{V} = \mathbf{V}_a + \mathbf{V}_p \tag{2}$$

Note the quantities above are three-dimensional velocity vectors. Each component of the three-dimensional velocity vector can be expressed

$$\mathbf{u} = \mathbf{u}_a + \mathbf{u}_p \tag{3a}$$
$$\mathbf{v} = \mathbf{v}_a + \mathbf{v}_p \tag{b}$$
$$\mathbf{w} = \mathbf{w}_a + \mathbf{w}_p \tag{c}$$

where:
$\mathbf{u}$, $\mathbf{v}$, $\mathbf{w}$ = velocity of air wrt Earth
$\mathbf{u}_a$, $\mathbf{v}_a$, $\mathbf{w}_a$ = velocity of air wrt aircraft
$\mathbf{u}_p$, $\mathbf{v}_p$, $\mathbf{w}_p$ = velocity of aircraft wrt Earth

The aircraft coordinate system, the Earth-centered coordinate system, attitude angles, and angles of attack and sideslip are shown in Fig. 1.

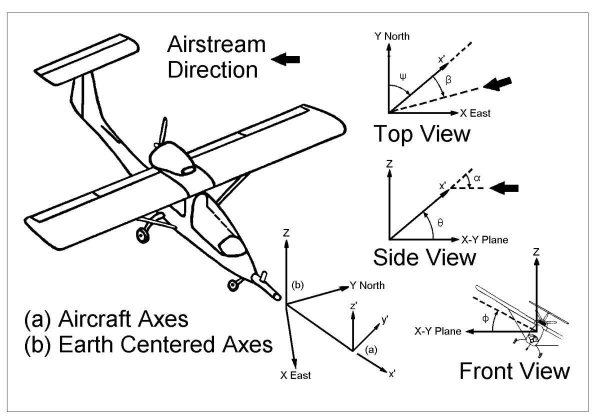

Fig. 1. Aircraft coordinate system.

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The aircraft uses the "Best Aircraft Turbulence" (BAT) probe for measuring atmospheric turbulence (Hacker and Crawford 1999). The BAT probe uses a hemispherical 9-hole pressure sphere to measure $\mathbf{u}_a$, $\mathbf{v}_a$, $\mathbf{w}_a$ and static pressure (P_s) using four differential pressure transducers. High-frequency probe motion is measured with an array of three orthogonal accelerometers. The accelerometer package is located at the center of the sphere, which coincides with the center of the aircraft coordinate system. The probe also uses two microbead temperature sensing elements (T_{air}) to measure air temperature with a response time of 0.07 s. A platinum resistance thermometer (T_{bar}) is used for a mean air temperature reference.

Measurements of $\mathbf{u}_p$, $\mathbf{v}_p$, and $\mathbf{w}_p$ are made using a combination of GPS velocity measurements and data from a set of three orthogonal accelerometers mounted at the center of gravity of the aircraft. A NovAtel model 3151 GPS is used to measure the horizontal position, altitude above the reference geoid, and three-dimensional velocity of the aircraft with respect to Earth. Each position, velocity, and altitude measurement by the NovAtel GPS is recorded at 10 Hz. The airborne GPS measurements are differentially corrected with data from a static ground station to improve the horizontal position measurement to within 5 m and the velocity measurement to within 2 cm s^{-1}.

Because velocity components $\mathbf{u}_a$, $\mathbf{v}_a$, and $\mathbf{w}_a$ are measured in an aircraft-centered coordinate system and $\mathbf{u}_p$, $\mathbf{v}_p$, and $\mathbf{w}_p$ are measured in an Earth-centered coordinate system, $\mathbf{u}_a$, $\mathbf{v}_a$, and $\mathbf{w}_a$ must be rotated to Earth coordinates before Eq. (3) can be applied. Hence, the attitude angles (θ, ϕ, ψ) of the aircraft must be measured. A Trimble Advanced Navigation System (TANS) GPS is used to measure aircraft attitude angles with an accuracy of $\pm 0.05^o$ at 10 Hz. Data from the two sets of three orthogonal accelerometers are used to supplement the TANS angles, allowing the frequency response to be extended to 50 Hz.

4. AIRCRAFT AND INSTRUMENTATION

The Sky Arrow is a two-seat aircraft powered by an 81-HP 4-cylinder, 4-stroke, horizontally opposed engine. The aircraft has a wingspan of 9.6 m, length of 8.2 m, wing area of 13.1 m^2, and a maximum takeoff mass of 648.6 kg. The structure is made of carbon fiber and epoxy resin.

Because the engine is mounted in a pusher configuration, the BAT probe can be mounted directly on the aircraft's nose, on the centerline of the aircraft. Mounting the probe in this location minimizes airflow contamination due to upwash and sidewash generated by the wing (Crawford *et al.* 1996).

The aircraft has a relatively slow flight speed of 30 m s^{-1}, allowing a horizontal spacing of 0.6 m between 50 Hz measurements in no-wind conditions. The aircraft has an endurance of 4 h, allowing flight distances of up to 430 km. Operating altitudes range from 10 m above ground level to more than 3500 m above sea level.

The aircraft has two seats, fore and aft, that may both be occupied by persons during research flights. The data acquisition system and instruments are carried below and behind the rear seat. A 355 mm diameter portal and a 255 mm x 255 mm portal are cut in the bottom of the aircraft for mounting downward looking instruments. Additionally, the aircraft is certified for normal-category operations under both FAA and JAR regulations.

A list of equipment carried aboard the aircraft for flux measurement flights follows:

Qty	Range	Resolution	Model	Freq
F_H_2O	-	10 mg m^{-3}	ATDD IRGA	50
F_CO_2	-	300 µg $^{-3}$	ATDD IRGA	50
S_H_2O	0-12 mmol mol^{-1}	0.02 mmol mol^{-1}	LiCor 6262	1
S_CO_2	300-400 mmol mol^{-1}	.1 µmol mol^{-1}	LiCor 6262	1
T_{dew}	±50°C	0.05°C	EdgeTech	1
T_{air}	±15°C	0.005°C	µbead	50
T_{bar}	±50°C	0.05°C	PRT	1
PAR_{up}	0-2400 µmol m^{-2} s^{-1}	1%	LiCor 200S	1
PAR_{dn}	0-2400 µmol m^{-2} s^{-1}	1%	LiCor 200S	1
R_n	-100/+1200 W m^{-2}	1%	REBS Q*7	1
T_{sfc}	-40/+1100°C	0.1°C	Everest 4000.4GH	50
Alt	0-1000 m	10 mm	Riegl LD90-3	50

A LiCor model 6262 CO_2/H_2O analyzer is used to measure H_2O and CO_2 concentrations at 1 Hz (S_H_2O & S_CO_2), while an open-path infrared gas analyzer (IRGA) is used to measure H_2O and CO_2 concentrations at 50 Hz (F_H_2O & F_CO_2) (Auble and Meyers 1992). Dew point temperature measurements are made using an EdgeTech DewTrack hygrometer (T_{dew}).

The aircraft is equipped with three radiation sensors. A Radiation Energy Balance Systems (REBS) Q*7 Fritschen net radiometer (R_n) is mounted on the aircraft's horizontal stabilizer and provides measurements of incoming and reflected short and long-wave solar radiation. Two LiCor model 200S pyranometers are mounted upward and downward to measure photosynthetically active radiation (PAR_{up} & PAR_{dn}) at wavelengths of 0.4-0.7 μm.

Earth surface temperature is measured using an Everest Interscience 4000.4GH infrared thermometer (T_{sfc}). Surface reflectivity characteristics are measured using an Exotech 4-band radiometer, which measures color intensities in the red, green, blue, and near infrared wavebands. A Riegl LD90-3 laser altimeter is used to measure the altitude of the aircraft above ground level (Alt).

5. DATA ACQUISITION SYSTEM

The data acquisition system used in the aircraft is built using an Intel Celeron® microprocessor and assorted IBM-PC compatible computer hardware. The primary interface between the data acquisition equipment and the computer is by means of two multiport serial cards installed in the PC.

Two 16 channel analog data acquisition modules are used to measure 32 analog channels. The analog-to-digital (A/D) conversion is performed by a 16-bit A/D converter, which is triggered by a low-voltage trigger pulse. Receipt of the trigger pulse begins a process where each channel is sampled 16 times and the data filtered with a Butterworth filter. One final value for each channel is then sent via RS-422 serial bus to the host computer for final storage. Since this entire process is completed in 19ms, sampling intervals of 20 ms (50 Hz) are possible. A Quatech dual-port high-speed serial interface card is used to service the data from the remote A/D modules.

The data acquisition system also uses a 4-port Digi ClassicBoard multiport serial card to service data from other serial devices. Devices which use this serial card are the Riegl laser altimeter, the NovAtel GPS, and the TANS GPS.

Data acquired from the remote A/D modules and the laser altimeter are synchronized in time by the use of low-voltage 50 Hz triggers generated by the NovAtel GPS. The data acquisition system master clock is a 1 pulse-per-second low-voltage trigger generated by the NovAtel GPS to provide real-time updates of the GPS time. All incoming data are synchronized in time by the data acquisition program and stored in a binary data file.

Following a flight, differential corrections are performed on the GPS position and velocity data. The differential correction data are then inserted into a new file, along with the data collected onboard the aircraft. During this step, the file format is changed to a network Common Data Format (netCDF) file (Rew *et al.* 1997). Data are quality controlled during this step to remove spikes and flag data of poor quality.

Calculation of the $\mathbf{V}_a$, $\mathbf{V}_p$, and $\mathbf{V}$ vectors are performed using techniques described in Crawford *et al.* 1992 and Eckman *et al.* 1999.

6. WIND SYSTEM PERFORMANCE

Calibration of the wind system is performed using data from several quasi-static and dynamic oscillatory maneuvers performed in still air over the Arctic Ocean north of Barrow, AK, USA. A series of pitching and yawing maneuvers was conducted to ensure time synchronization of the data acquisition system and instruments used to measure the constituents of the vectors of Eq. (3) (Bögel and Bauman 1991; Scott *et al.* 1990). The calibration maneuvers were also used to help determine offsets between the axes of the TANS GPS attitude system and the axes of the orthogonal accelerometers located in the BAT probe and at the aircraft center of gravity.

One approach to finding appropriate calibration offsets is an iterative one which uses a downhill-simplex routine (Press *et al.* 1986) to find the minima of a characteristic function. We have defined a characteristic function as a "composite" of the standard deviations of **u**, **v**, and **w**.

$$\sigma_c = \sqrt{\sigma_u{}^2 + \sigma_v{}^2 + \sigma_w{}^2} \tag{4}$$

where:
σ_c = composite wind standard deviation
σ_u = standard deviation of east wind wrt Earth.
σ_v = standard deviation of north wind wrt Earth.
σ_w = standard deviation of vertical wind wrt Earth.

The characteristic function is used to quantify the performance of the horizontal and vertical winds, as it is a measure of the total uncertainty of the wind measurement.

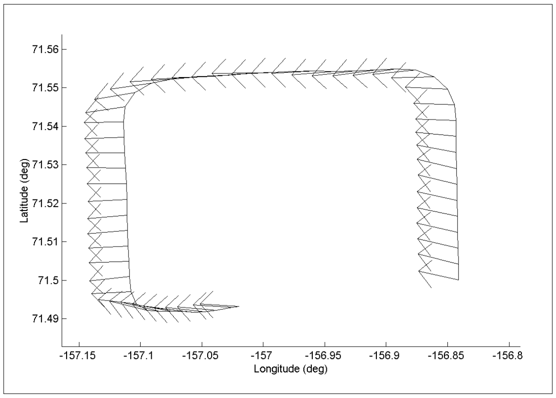

Fig. 2. Wind barb plot for a 3.5 sided box pattern.

Figure 2 shows a latitude versus longitude plot of 3.5 legs of a box pattern flown in smooth air north of Barrow, AK, USA. The altitude of the box was constant, with standard rate turns (3° s^{-1}) at the corners. The barbs indicate magnitude and direction of the wind at 12 second intervals for the 613 sec maneuver. Winds reported by Barrow Flight Service for the period were 60° magnetic (84° true), at 8 m s^{-1}. Statistics are shown below:

	Mean	Std-Dev	Minimum	Maximum
Magnitude	9.7340	0.3061	9.1330	10.4583
Direction	89.4297	2.3407	84.8028	93.7438

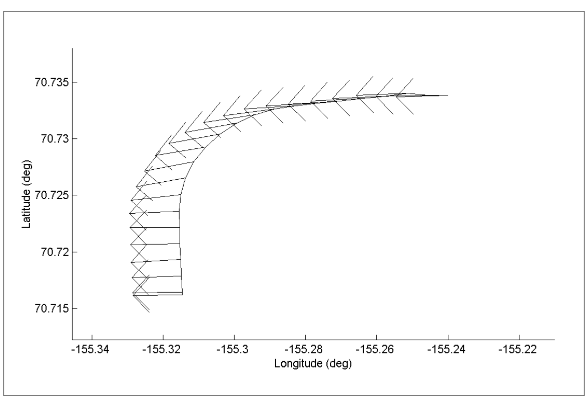

Fig. 3. Closeup of NW corner of box pattern shown in Fig. 2.

Figure 3 shows an enlargement of the turn in the northwest corner of the wind box shown in Fig. 2. The barbs indicate magnitude and direction of the wind at 4 second intervals. The duration for this portion of the maneuver is 100 sec. A table of selected statistics follows:

	Mean	Std-Dev	Minimum	Maximum
Magnitude	9.6774	0.1831	9.3820	9.9456
Direction	91.5281	1.1353	89.8125	93.7438

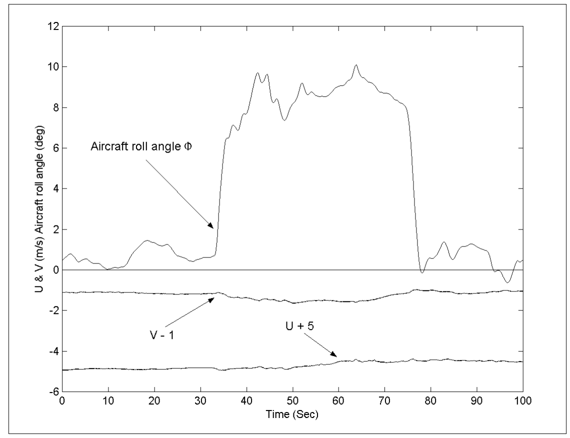

Fig. 4. Vectors **u** and **v** and roll angle ϕ during the turn shown in Fig. 3.

Figure 4 shows a time series of the vectors **u** and **v** and the roll angle ϕ for the turn shown in Fig. 3. Note that **u** is offset by +5 and **v** is offset by -1 for clarity. Performance of the wind system during turns is quite good, as shown by the standard deviations of the magnitude and direction of 0.1831 and 1.1353, respectively.

The performance of the wind system when measuring vertical winds was also considered. In this case, a dynamic pitching maneuver was performed at varying frequencies so that the quality of the vertical winds could be measured while the aircraft was being maneuvered. The periods of the two maneuvers are 50 sec and 25 sec, corresponding to pitching frequencies of 0.02 Hz and 0.04 Hz, respectively. Since an independent measurement of the vertical wind component does not exist for this particular test, the suitability of the flying conditions for the dynamic pitching test were subjectively determined by the pilot.

The following table shows statistics for the vertical wind component w during a 250 sec portion of the flight, encompassing both the 50 sec period and the 25 sec period maneuvers:

	Magnitude	Std-Dev	Minimum	Maximum
w	0.1912	0.3006	-0.5020	1.0235

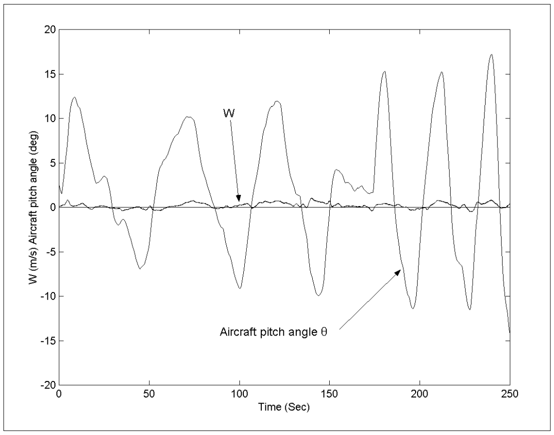

Fig. 5.Vertical wind component w and aircraft pitch angle θ during dynamic pitch maneuvers.

Figure 5 shows a time series of the vertical wind component w and the pitch angle of the aircraft, θ. The calibration flight was performed on July 13, 2000. Weather conditions observed by Barrow Flight Service during the flight were visibility > 20 km, a few clouds at 2100 m, air temperature of 3°C, dew point of 0°C, and sea level atmospheric pressure of 1020.6 mb.

7. CONCLUSIONS

A Sky Arrow aircraft was instrumented to measure fluxes of sensible heat, latent heat, and CO_2. The wind measurement system was installed in the aircraft and performance tested using in-flight calibration maneuvers. Supplemental instruments were installed on the aircraft to provide radiation and surface characteristic measurements. Horizontal winds measured during box maneuvers show good agreement with data from Barrow Flight Service. Vertical winds measured during dynamic pitching maneuvers were found to be reasonable for the flight test conditions. Based on these test results, the Sky Arrow promises to be a viable platform for measurement of boundary layer fluxes.

8. REFERENCES

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